Solar Photovoltaic Power-to-Heat-to-Power Energy Storage

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Abstract

This article summarizes part of the work developed, and already published, in the context of the AMADEUS project (www.amadeus-project.eu), a FET-OPEN project funded by the European Commission to research a new generation of materials and solid state devices for ultra-high temperature energy storage and conversion. New silicon-based alloys as new phase change materials (PCMs) are explored, achieving latent heat in the range of 1000-2000 kWh/m^3, which means an order of magnitude greater than that of typical salt-based PCMs used in concentrated solar power (CSP). In addition, silicon-based PCMs lead to storage temperatures well beyond 1000 ºC, and so this project aims at breaking the mark of ~ 600 ºC rarely exceeded by current state of the art thermal energy storage (TES). Furthermore, this article presents the most significant outcomes of work developed to assesses whether it is profitable to store solar photovoltaic (PV) electricity in the form of heat and convert it back to electricity on demand in the residential sector.

1. Introduction

Greater penetration of renewable energy sources is necessary to address some of the major challenges that the present world economy faces: energy security, pollution, sustainability and climate change [1]. Reaching the climate goals of the Paris agreement (2015) will require increasing quantities of renewable energy to be generated in the urban environment and the availability of energy storage technologies at competitive cost structures. The latter is essential in order to manage a future electric system based on renewables.

This paper contains part of the work, already published [2,3], developed in the context of the AMADEUS project (www.amadeus-project.eu). Firstly, it presents a novel latent heat thermal energy storage (LHTES) system that has the potential to achieve one of the highest energy densities among existing energy storage solutions. Secondly, the most significant outcomes of work developed to assesses whether it is profitable to store solar photovoltaic (PV) electricity in the form of heat and convert it back to electricity on demand in the residential sector is presented.

The proposed LHTES stores power in the form of heat, which can be converted back to power when necessary (power-to-heat-to-power). This LHTES considers silicon-based alloys as new phase change materials (PCMs) combined with novel solid-state heat to power conversion technologies able to operate at temperatures above 1000 °C, in particular hybrid ther-

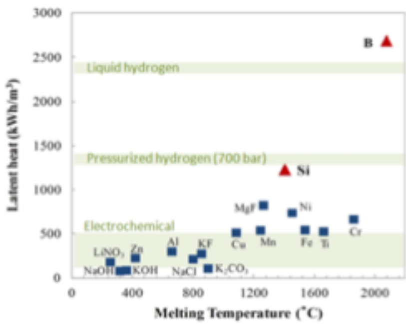

Figure 1. Latent heat of fusion of different materials as a function of the melting temperature

mionic-photovoltaic (TIPV) devices. Silicon-based alloys latent heat falls within the range of 1000-2000 kWh/m^3 and melting points far above 1000 °C. In Figure 1 the latent heat of fusion of different materials as a function of the melting temperature is shown. This figure illustrates the potential of silicon (1230 kWh/m^3) and boron (2680 kWh/m^3) compared with latent heats of typical salts used in CSP, such as $NaNO_3$ (110 kWh/m^3) and KNO_3 (156 kWh/m^3). Figure 1 also shows that silicon and boron PCMs provide higher storage energy densities than most forms of energy storage, including electrochemical batteries and pressurized hydrogen.

The main challenge of the proposed LHTES solution is the very high operating temperature, especially concerning the heat-to-power conversion system (TIPV device). Nonetheless, solid state converters, such as thermionics [4], thermophotovoltaics (TPV) [5,6] and hybrid thermionic-photovoltaics [7], are perfectly suited for such high temperatures, mainly because they are based on the direct emission of electrons and photons through space (non-direct contact), eliminating the need for a working fluid and moving parts. These converters also benefit from extremely high-power densities (power-to-weight and power-to-volume ratio), low maintenance costs due to the absence of moving parts, and silent operation. The latter is relevant for energy storage applications in an urban environment. Figure 2 presents a sketch of the LHTES concept

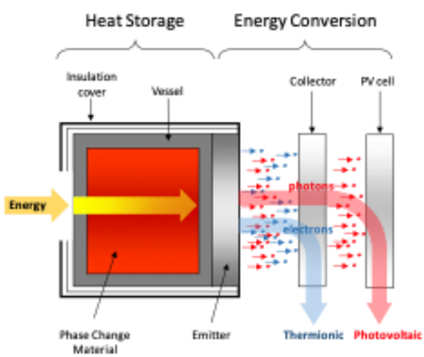

Figure 2. Sketch of the AMADEUS LHTES concept

developed in the AMA-DEUS project. It can be observed how part of the energy storage will be converted into electricity by a hybrid TIPV device, while the remaining part is delivered in the form of heat (e.g. it could be used for hot water and/or heating appliances).

1.1. AMADEUS project

AMADEUS is a FET-OPEN research project funded by the European Commission for the development of a new generation of ultra-compact energy storage devices based on molten silicon and solid-state heat-to-power converters [8]. The AMADEUS project final aim is to demonstrate the proof-of-concept of a new LHTES based on ultra-high temperature PCMs and solid-state heat-to-power converters. In order to reach the final goal of the project, a number of materials and technologies have been investigated, and two proofs of concept are scheduled:

- Novel PCMs based on the silicon-boron system with ultra-high melting point and latent heat,
- Novel refractory lining composites based on carbides, nitrides and oxides for the PCM container walls,
- Advanced thermally insulated PCM casing enabling small heat losses,
- Proof of concept of a novel hybrid thermionic-photovoltaic (TIPV) device [7],
- Proof of concept of the final complete LHTES device comprising the elements described above.

The project is subdivided into two main blocks: developing a high temperature heat storage unit and developing a high temperature energy conversion module. The first block comprises the study of silicon-boron PCMs, PCM-container interaction, heat transfer analysis in the PCM and thermal insulation. The research work on this first block is being developed at FRI and NTNU [8] and first results of this research can be found in [9,10,11]. The second block of the project studies the high temperature operation of TIPV converters. All of the advances performed over the first years of the project will serve as a basis for the design and construction of a LHTES prototype during the last year of the project, which will allow demonstration of a proof of concept for the complete system. Analysis of the complex heat transfer mechanisms occurring inside the proposed PCM have being developed on the basis of the ANSYS® Fluent platform by CERTH [12]. Regarding heat transfer analysis of the overall system, a CFD model has been developed in COMSOL® [13]. Finally, energy conversion block activities are devoted to the proof of concept of the novel thermionic-photovoltaic (TIPV) device [7]. While both technologies (thermionic -TI- and thermophotovoltaic -TPV-) have been demonstrated separately by researchers participating in the project [14,15], the hybrid TIPV device has only been considered theoretically [7]. The TIPV device (Fig. 3) consist of a tandem arrangement between a thermionic and a photovoltaic cell, comprising two main elements: the TIPV cathode (or emitter) and the TIPV anode. The TIPV cathode is the radiating element; it irradiates electrons and photons when heated due to a low work function and high optical emissivity. The TIPV anode comprises the thermionic collector and the TPV cell; the former will absorb the electrons and the TPV cell will absorb the emitted photons,

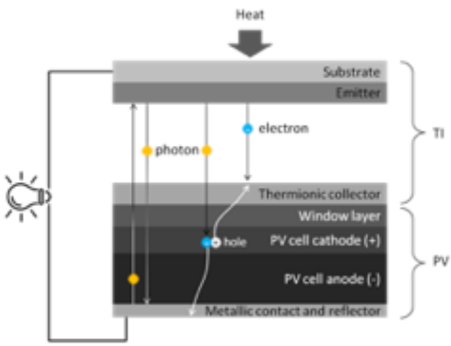

Figure 3. The thermionic-photovoltaic (TIPV) device

generating an electron-hole pair. Electrons collected in the thermionic collector recom-bine with holes photo-generated in the TPV cell; thus, closing the circuit and series connec-ting the thermionic and photovoltaic sub-devices. Finally, the emitter and the TPV cell anode are externally connected to deliver external electrical power. The combination of both devices is expected to provide a significant increment of the power density compared with the independent thermionic and photovoltaic devices.

2. Lab-Scale Prototype

2.1. System model

In order to define the LHTES prototype design, a number of possible configurations have been modelled and analyzed; aiming for the best compromise in performance and simplicity at lab-scale. The problem definition (materials selection, thermal and mechanical analysis) was addressed, followed by a Computational Fluid-Dynamic (CFD) analysis in both steady-state and transient scenarios. Finally, on the basis of modelling results, analysis and discussion, a final prototype design has been proposed, that aims to maximize a merit function defined as the quotient between the radiated power towards the TIPV converter and the overall heat losses (Prad/Ptot).

The design proposed for the LHTES prototype is sketched in Figure 4; where the different elements and materials are indicated. The overall dimensions of the prototype are 40 cm

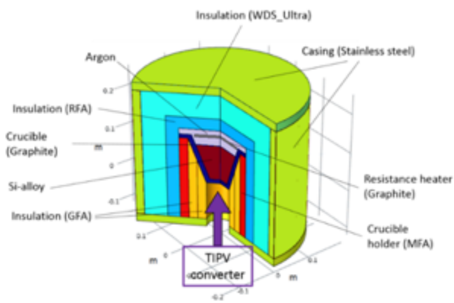

Figure 4. Proposed design and materials for the LHTES prototype

diameter and 37 cm high; the volume of silicon-alloy contained in the crucible is 0.5 L (~ 1.16 Kg Si). The external casing of the prototype is made of stainless steel. Graphite fiber board (RFA), fumed silica board (WDS Ultra) and graphite fiber mat (GFA) are considered as possible insulation materials. The crucible holder is made of a rigid graphite fiber board (MFA), and the crucible is made of high-density graphite. For the heat input during the charging stage of the prototype a graphite resistance heater was selected.

Relevant properties of the selected materials considered for the CFD simulations conducted are presented in Table 1; except for the thermo-chemical properties of the Si-alloy that are presented in Table 2.

In Figure 5 (left) the boundary conditions (BCs) and the heat transfer mechanisms for the thermal modelling are indicated. Conduction, convection and radiation phenomena are evaluated, accordingly, at all boundaries and in all volumes. BCs for the structural mechanical modelling are presented in Figure 5 (right). It can be observed that the insulation elements effect is disregarded (those are considered flexible) and that the remaining surfaces BCs are divided between free displacement and fixed boundaries.

Material	**Thermal conductivity, k [W/(K·m)]**		**Max. operation temperature [ºC]**	**Thermal expansion, α [m/K]**
	T = 25 ºC	**T > 1000 º C**		
WDS	0.034	-	1000	-
RFA	-	0.3	2000	-
GFA	-	0.5	2200	-
MFA	-	.03	2000	-
Graphite	1.7	3.2	>2500	3.5 e-6
Stainless steel	240	-	940	2.4 e-5
Argon (gas)	0.02	0.05	-	-

Table 1. Properties of the LHTES prototype involved materials

Property	Temperature [°C]		Phase change ($T = T_m$)
	$T < T_m$	$T > T_m$	
Density, ρ [kg/m³]	2535	2520	-
Thermal conductivity, k [W/(K·m)]	25	50	-
Heat capacity, C_p [J/(kg·K)]	1040	1040	-
Dynamic viscosity, μ [kg/(m·s)]	-	0.06	-
Latent heat, L [J/kg]	-	-	1.8×10^6
Thermal expansion coef., α [m/K]	2.6×10^{-6}	-	-
Emissivity, ε [-]	0.7	0.2	-

Table 2. Thermo-physical properties of pure silicon (T_m=1414 °C), which is selected as the PCM for this model

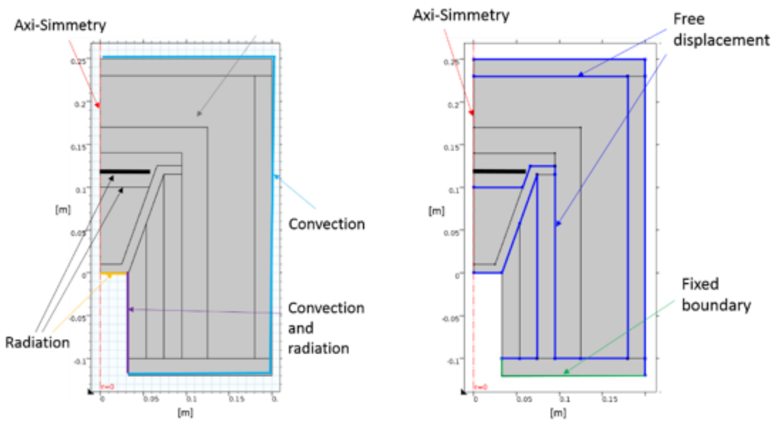

Figure 5. Boundary conditions and heat transfer mechanisms for the thermal calculations in the model (left), and BCs for the structural analysis modelling (right). Axi-symmetric view of the prototype

2.1. Steady-state and dynamic analyses

Steady-state calculations are conducted for the most demanding conditions during the prototype operation (prototype is fully charged), thus, when all the silicon-based PCM is melted. In Figure 6 (left), the temperature distribution of the LHTES prototype at this time is presented. The highest temperatures are at the heating element (1567 ºC) and top surface of the silicon-alloy (1511 ºC), and the temperature of the radiant surface towards the TIPV device (crucible bottom surface) is about 1103 ºC. In Figure 6 (right), results of the thermal and structural mechanics analysis combined are presented. The von Mises stress criteria is used to evaluate whether the different materials will yield when subjected to the strains associated with thermal expansion [16].

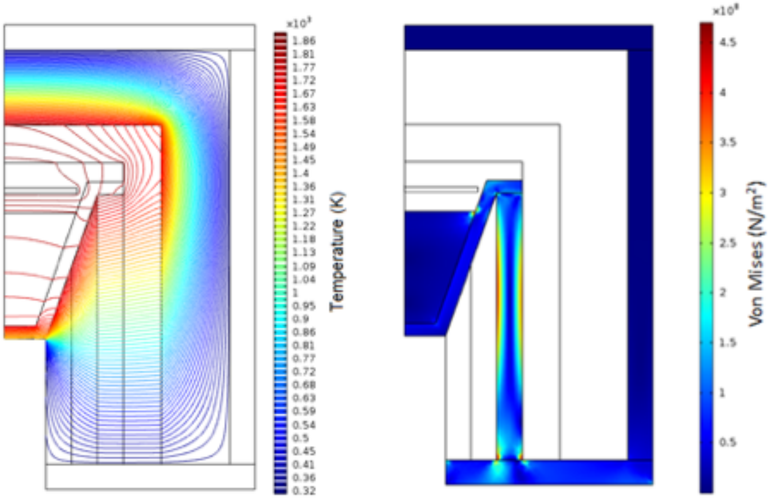

Figure 6. Temperature distribution (left) and Von Misses (structural mechanics analysis) when the system is fully charged (all Si-based PCM melted)

As mentioned above, this design was optimized aiming to maximize the merit function Prad/Ptot (expressed in percentage); which is obtained to be 62.9 %. This means that 62.9 % of the storage energy is available for the subsequent conversion by means of the TIPV device. It is worth mentioning that scaling up the system will result in significantly lower heat losses through the outer wall, due to the lower surface-to-volume ratio. For a real LHTES, Prad/Ptot ratios above 75-85 % are considered feasible (and above 90 % desirable) when scaling up the system and optimizing its design at the same time.

By means of transient simulations the discharge of the LHTES prototype was also modelled. The interest is in analyzing the temperature distribution, the length of the discharge periods and the rate of power generated.

In Figure 7, the temperature distribution along the vertical axis in the Si-alloy and crucible during discharge is presented; discharge takes 80 minutes. The silicon bottom (crucible bottom) temperature goes from 1414 to 1337ºC (1103 to 1072ºC), and according to an in-house (idealized) TPV model based on InGaAsSb semiconductor devices (bandgap of 0.51 eV), this is translated to a power generation per unit area in the range 3.85-2.94 W/cm^2 [17]. It must be noticed the important drawback of the large temperature gradient in the crucible. If TPV cells were operated at 1414 ºC (temperature at point A in the inset of Figure 7), the power generation density (watts per unit of device area) would be as high as 11.4 W/cm^2 [17]. Besides, this power could be doubled by using TIPV instead of TPV up to ~20 W/cm^2 (1000 times greater than conventional solar PV cells) [7].

3. Potential applications

Thermal energy storage for power generation is almost exclusively used in concentrated solar power (CSP) systems, where the sun's

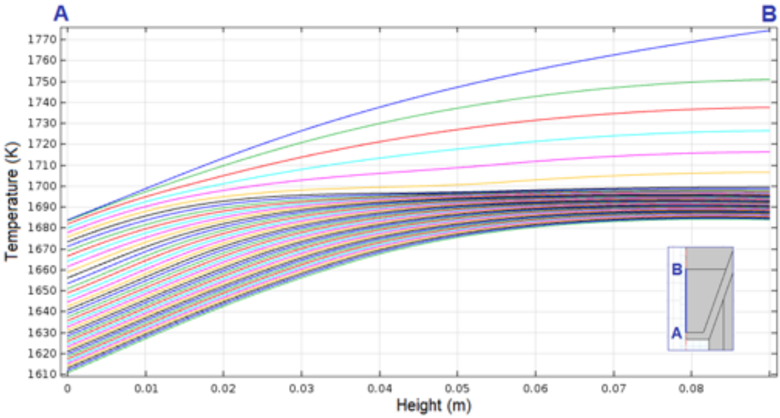

Figure 7. Temperature distribution along vertical axis in the crucible during discharge (time step: 120 sec)

energy is stored in the form of sensible heat in molten salts and converted upon demand into electricity using a conventional Rankine engine. The ultra-high energy density of molten silicon also opens the door to a new kind of application for thermal energy storage, which is the direct storage of electricity using an electric furnace for melting. Although thermodynamically counterintuitive, the extremely low prices of the electricity produced by renewable sources, such as wind and solar, are suggesting that using electricity for heating will become more economical than burning fuels. In this scenario, the proposed LHTES system could be used for electricity storage and co- or tri-generation in domestic applications (electricity/heating and electricity/heating/cooling). Besides, many other applications may appear in the future, including waste heat storage and recovery in industrial processes, space power storage and conversion, etc. [2].

In principle, the proposed LHTES device could cover from a few kilowatts-hour (kWh) of capacity for domestic applications to some megawatts-hours (MWh) in the case of large accumulators.

The authors of this work have also published in [3] further research work evaluating the implementation of a power-to-heat-to-power storage solution for the self-consumption of solar PV electricity in a dwelling in Madrid. In particular, assessing whether it is profitable to store solar PV electricity in the form of heat and convert it back to electricity on demand. Considering a number of technical and economic parameters, the proposed and studied solution comprises two kinds of heat stores: a low- or medium-grade heat store for domestic hot water and space heating, and a high-grade heat store for combined heat and power generation (silicon-based LHTES). Two cases are considered where the energy that is wasted during the conversion of heat into electricity is employed to satisfy either the heating demand, or both heating and cooling demands by using a thermally-driven heat pump. The comparison of these solutions against a reference case that relies on the consumption of grid electricity and natural gas and uses an electrically-driven heat pump for cooling is conducted. The results show that, under relatively favourable conditions, the proposed solution that uses an electrically-driven heat pump could provide electricity savings in the range of 70-90 % with a payback period of 12-15 years, plus an additional 10-20 % reduction in the fuel consumption. Shorter payback periods, lower than 10 years, could be attained by using a highly efficient thermally driven heat pump, at the expense of increasing the fuel consumption and the greenhouse gas emissions. Hybridising this solution with solar thermal heating could enable significant savings on the global emissions, whilst keeping a high amount of savings in grid electricity (> 70 %) and a reasonably short payback period (< 12 years) [3].

4. Conclusions

This article summarizes part of the work developed, and already published, in the context of the AMADEUS project towards a solar photovoltaic (PV) power-to-heat-to-power energy storage solution. The main advantage of the concept relies on the extremely high latent heat of silicon and silicon alloys (~1200 kWh/m^3) that clearly surpass most forms of energy storage, including batteries (< 500 kWh/m^3) and molten salts (<100 kWh/m^3).

From CFD modelling and simulation of a small lab-scale prototype of a LHTES, relevant information about heat losses, materials and operation conditions of the proposed solution are obtained. The lab-prototype contains 0.5 litres of silicon, representing a latent heat storage capacity of ~ 615 Whth. According to CFD simulations, solidification of silicon will last about 80 min, during which ~ 63 % of the latent heat will be delivered as radiation towards the solid-state energy converter, which will convert part of this radiation into electricity. Assuming a conversion efficiency of 40 %, it means that 25 % of the stored latent heat will be retrieved as electricity. This relatively low conversion efficiency is mostly attributed to the small dimensions of the lab-scale prototype, characterized by a large surface-to-volume ratio that results in relatively large losses through the thermal insulation. Scaling up the system is expected to produce conversion efficiencies in the range of 30-40 %;

Examples of possible applications range from a few kilowatt-hour (kWh) of capacity to some megawatt-hours (MWh), in the case of large accumulators. The proposed system could be used for electricity storage (using electric furnaces) for co- or tri-generation in domestic applications, direct solar energy storage (CSP), and energy storage at industrial waste heat recovery systems, among many others.

Finally, research work evaluating the implementation of a power-to-heat-to-power storage (LHTES) solution for the self-consumption of solar PV electricity in an urban environment has also been conducted. Results indicate, that under relatively favourable conditions, the proposed solution could provide electricity savings in the range of 70-90 % with a payback period of 12-15 years, plus an additional 10-20 % reduction in the fuel consumption.

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